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(71) Applicant: TRUSI TECHNOLOGIES, LLC [US/US]; 657 N. Pastoria Avenue, Sunnyvale, CA 94086 (US).

(72) Inventors: SINIAGUINE, Oleg; 1247 Weibel Way, San Jose, CA 95125 (US). BAGRIY, Igor; 1220 North Fair Oaks Ave., Apt. 1307, Sunnyvale, CA 94089 (US).

(74) Agents: SHENKER, Michael et al.; Skjerven, Morrill, MacPherson, Franklin & Friel LLP, 25 Metro Drive, Suite 700, San Jose, CA 95110 (US).

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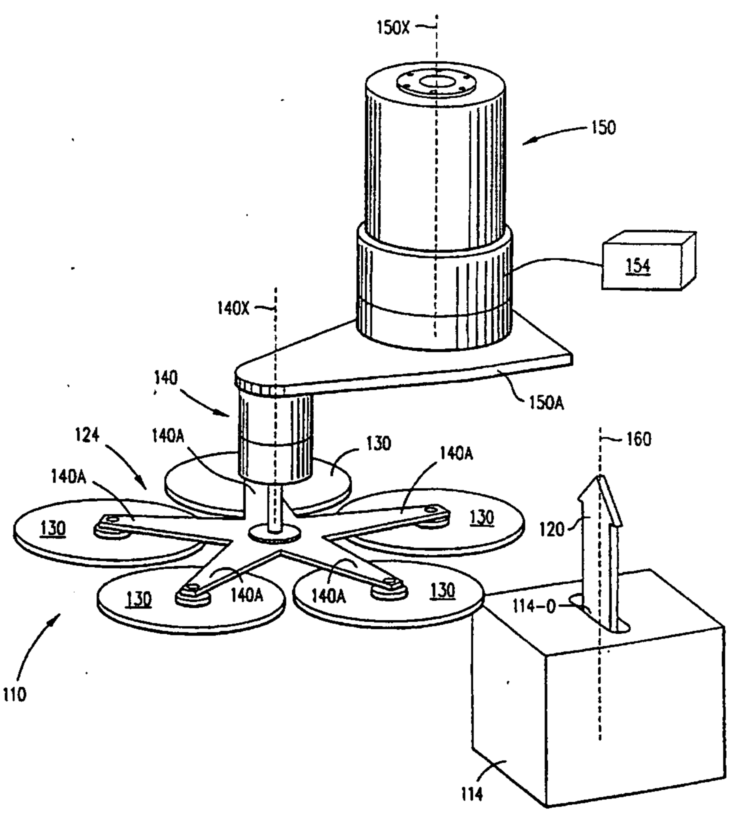
(54) Title: PLASMA PROCESSING METHODS AND APPARATUS

(57) Abstract

To move an article in and out of plasma during plasma processing, the article is rotated by a first drive around a first axis, and the first drive is itself rotated by a second drive, so that the article enters the plasma at different angles for different positions of the first axis. The plasma cross–section at the level at which the plasma contacts the article is such that those points on the article that move at a greater linear velocity (due to being farther from the first axis) move longer distances through the plasma. As a result, the plasma processing time becomes more uniform for different points on the article surface. The direction of rotation of the first and/or second drive changes during processing to improve processing uniformity. The article is allowed to be processed with the plasma only during one–half of each revolution of the second drive. In the other half of each revolution, the processing is substantially prevented by increasing the second drive velocity as the article is carried through the plasma.



PLASMA PROCESSING METHODS AND APPARATUS

BACKGROUND OF THE INVENTION

The present invention relates to processing of materials, and more particularly to plasma processing.

Plasma processing is widely used to modify surface properties of materials. Thus, plasma is used in fabrication of integrated circuits to perform deposition, etch, cleaning, and rapid thermal anneal. Plasma-based surface processes are also used for hardening of surgical instruments and machine tools, and are used in aerospace, automotive, steel, biomedical, and toxic waste management industries. See, for example, M.A. Lieberman and A.J. Lichtenberg, "Principles of Plasma Discharges and Materials Processing" (1994), page 1.

A common goal in a plasma-based process design is uniform treatment of the target surface (i.e. the surface treated with plasma). It is desirable to develop systems in which the uniform processing is facilitated.

In some systems, the target article and the plasma move relative to each other, and it is desirable to facilitate precise control of this relative movement. Further, it is desirable to reduce stresses on the target articles thus reducing the possibility of damaging the target articles.

SUMMARY

Some embodiments of the present invention provide methods and apparatus for moving the target articles relative to the plasma so as to facilitate uniform processing of the target surfaces. In particular, some embodiments facilitate precise control of the movement of the articles relative to the plasma by reducing accelerations of the articles. Reducing the accelerations also results in reduction of stresses to which the articles are subjected.

As the target article moves through the plasma, the article velocity may have to be varied to achieve uniform

note, if the processing occurs at atmospheric pressure (as does DPT), even constant-velocity movement of the plasma source can make the plasma difficult to control unless the plasma motion is very slow. Thus, it is desirable to reduce the velocity and acceleration of the plasma source, preferable down to zero.

Accordingly, in some embodiments of the present invention, target surface points that move at different velocities are caused to travel different distances through the plasma so that the faster moving points travel a longer distance. As a result, the time spent in the plasma by faster moving points approaches the time spent by slower moving points. Consequently, the accelerations needed to make the plasma processing uniform are reduced.

In some embodiments, the plasma source is stationary.

In some embodiments, these advantages are achieved as follows. The plasma flow cross-section through which the target article moves is made to have different dimensions in different directions. The target article passes through the plasma multiple times in different directions so that the points moving faster intersect the plasma along a longer dimension of the cross-section than the slower moving points. As a result, uniform treatment can be obtained with less variation of the article velocity.

In some embodiments, the plasma source is stationary. Changing the direction in which the target article intersects the plasma is achieved by rotating the drive that rotates the article so that the article rotates around a first axis which itself rotates around a second axis. The directions change because the article intersects the plasma at different positions of the first axis.

In some embodiments, the article rotates, and the direction of rotation is changed during processing. When plasma processing takes place at a high pressure (for example, atmospheric pressure), plasma becomes unstable when the article enters the plasma. As a result, the article edge points that enter the plasma are processed at a lower rate than the rest of

Figs. 14 and 15 show velocity graphs for the system of Fig. 1.

DESCRIPTION OF PREFERRED EMBODIMENTS

In plasma processing system 110 (Fig. 1) plasma source 114 generates plasma jet 120 schematically shown by an arrow. Plasma jet 120 flows vertically upwards through an elongated opening 114-O in source 114. The opening 114-O is elliptical in some embodiments. Horizontal cross sections of plasma jet 120 are also elliptical. In some embodiments, the opening 114-O and the plasma horizontal cross sections have a shape of an elongated rectangle, perhaps with rounded corners.

Carrousel 124 includes five holders 130. Each holder 130 holds an article 134 (Fig. 2) whose bottom surface is processed by plasma jet 120. Articles 134 in Figs. 1-5 are round semiconductor wafers whose flat horizontal bottom surfaces are processed with plasma 120. In some embodiments, the articles are not round and/or are not semiconductor articles. In some semiconductor-wafer embodiments, holders 130 are non-contact wafer holders such as described, for example, in PCT publication WO 96/21943 "Device For Treating Planar Elements With A Plasma Jet" published July 18, 1996 (inventors I. M. Tokmulin et al.) incorporated herein by reference. In some such embodiments, the plasma processing takes place at atmospheric pressure or at some other pressure close to the atmospheric pressure.

In some embodiments, wafer holders 130 hold the wafers by vacuum or by electrostatic, mechanical, or some other means.

Some embodiments of system 110 have only one holder 130, or some other number of holders.

Each wafer holder 130 is attached to an arm 140A of a first angle drive 140. Angle drive 140 rotates the wafers around vertical axis 140X.

Angle drive 140 is attached to arm 150A of second angle drive 150. Drive 150 rotates around vertical axis 150X.

described, W1 is a constant velocity of about 5 to 30 revolutions per second, and W2 is much smaller, the average value of W2 being at least 10 times smaller than W1 in some embodiments.

Dynamic plasma treatment is also described in the following articles incorporated herein by reference: P.P. Kulik, "Dynamic Plasma Treatment (DPT) of a Surface of a Solid Body", Plazmohimiya-87, Part 2 (U.S.S.R. Academy of Science, Institut Neftehimicheskogo Sinteza im. A.V. Topchieva, Moscow, 1987), pages 4-13; Yu. M. Agrikov et al., "Foundations of a Realization of a Method of Dynamic Plasma Treatment of a Surface of a Solid Body" (same publication, pages 58-96.)

In some embodiments the plasma processing is performed in vacuum.

Figs. 1-4 use the following notation:

Numeral 160 denotes a vertical axis that passes through the center of the opening 114-O and plasma jet 120. Axis 160 is a symmetry axis of the opening 114-O, the plasma jet 120, and plasma source 114.

R1 is the distance between axis 140X and the nearest edge point 134C of wafer 134 (all the distances in Figs. 2-4 are taken between the parallel projections of respective points onto a horizontal plane unless mentioned otherwise).

LS is the distance between the axis 140X and the farthest edge point 134F of wafer 134.

R2 is the distance between the axes 140X and 150X.

LP is the distance between axis 150X and axis 160 of plasma jet 120.

120F denotes the horizontal cross section of plasma jet 120 at the level of the lower surface of wafer 134. This cross section is called a "plasma footprint" below. The long axis of this elliptical footprint is shown at 210; the short axis is shown at 214. Axis 214 is perpendicular to axis 210.

Short axis 214 lies on axis 220 which intersects the axes 160, 150X in the top view of Figs. 2-4.

As illustrated in Figs. 2-5, as the arm 150A approaches plasma jet 120 (the angle Θ increases), the intersection of plasma footprint 120F with the wafer 134 approaches the point 134C and axis 140X. In Fig. 5, the ellipse 120F1 shows the position of plasma footprint 120F relative to wafer 134 when $\Theta = \Theta 1$ (Fig. 3). In that position, the plasma footprint covers the point 134F. The ellipse 120F2 shows the plasma footprint position at $\Theta = \Theta 2$ (Fig. 4). In that position, plasma footprint 120F covers the point 134C. Ellipse 120F3 shows the position of the plasma footprint 120F when Θ has an intermediate value between $\Theta 1$ and $\Theta 2$.

As the plasma footprint moves closer to point 134C and to axis 140X, the plasma processes wafer points having lower linear velocities. Indeed, the linear velocity relative to axis 140X (corresponding to the angular velocity W1) decreases because the distance from axis 140X decreases. Since angular velocity W1 is considerably higher than W2, the linear velocity component corresponding to W1 dominates the point's resultant linear velocity. In addition, as the angle Θ increases (see Figs. 2-4), the angle between the vector of the linear velocity relative to axis 140X and the linear velocity of axis 140X relative to axis 150X increases for points passing through the plasma. The increasing angle tends to further reduce the magnitude of the resultant linear velocity.

The decreasing linear velocity tends to increase the plasma processing time for points closer to the point 134C. However, the decreasing linear velocity is at least partially offset by the decreasing length of the points' trajectories through the plasma footprint. For example, the trajectory T2 of point 134C through ellipse 120F2 is shorter than the trajectory T3 of the point passing through the center of ellipse 120F3. The trajectory length decreases because the plasma footprint turns relative to the wafer so that as Θ increases from 0 to 180°, the angle between short axis 214 of the plasma footprint and the arm 140A increases from about 0

option I. Further, since drive 150 is not stopped, the processing time is less than in option I. In some embodiments, for Θ near 0, W2 is increased for 2 or 3 revolutions of drive 150, then W2 is decreased for a few revolutions of drive 150, then increased again. In some embodiments, for Θ values at which the wafers 130 intersect the plasma, W2 is the same in each revolution.

III. Velocity W1 of drive 140 is varied slightly (for example, by 0.1%) between different revolutions of drive 150.

The technique III is combined with I or II in some embodiments.

In some variations of techniques I, II, III, W2 and/or W1 are varied when Θ is near 180° and/or 0° and/or some other value.

The technique I has the advantage of allowing the wafer 130 to cool at least part of the way down to its original temperature after each revolution of drive 150, thus allowing the thermal conditions to be similar at each revolution. See PCT Publication WO 96/21943 published July 18, 1996, incorporated herein by reference. In some embodiments, the wafer is stopped for a few seconds at Θ = 0 to allow the wafer to cool. If the processing is sensitive to the thermal conditions, velocity W1 is controlled so that the wafer is allowed to cool during each revolution of drive 140.

In Figs. 2-4, the following relations hold true:

$$R1 \geq P1/2 \qquad (1)$$

that is, the distance R1 between the axis 140X and the nearest edge point 134C of wafer 134 is greater than or equal to one half of the length P1 of plasma footprint 120F.

This condition ensures in any revolution of first drive 140, any given point on wafer 134 passes through plasma 120 at most once. This is true even if the axis 140X is close to the axis 160. If the relation (1) did not hold, and the axis 140X were close to plasma 120, some wafer points (for example, 134C) could pass through the plasma twice in a single revolution of

If additional iterations are desired, the velocity W2 at each subsequent iteration can be determined similarly (the more material is removed at a given coordinate r during the previous iteration, the greater is the velocity W2(r) during the next iteration).

These iterations are programmed into the control system 154. In production, the control system 154 causes the system 110 to perform all the iterations.

Because wafer points traveling at a greater linear velocity tend to have longer trajectories through the plasma footprint 120F (see Fig. 5), uniform plasma processing can be achieved with less variation of the angular velocity W2 of drive 150. Fig. 6 illustrates this in one embodiment for a 200 mm wafer. The horizontal axis D_i is the distance between a wafer point P on diameter 134D and the point 134C. The top curve 610 shows the linear velocity V of the center of plasma footprint 120F (axis 160) relative to axis 140X. The velocity units are chosen so that V=1 at $D_i=0$. The velocity V was determined from velocity W2 which in turn was determined from the equations in the appendix.

The bottom curve 620 in Fig. 6 shows the linear velocity V for a prior art apparatus having only the angle drive 150. The first drive 140 is omitted. In that prior art apparatus, the distance between the axis 150X and the nearest wafer point 134C is R2+R1 where R2 and R1 are the dimensions for which the curve 610 was obtained. The linear velocity V was determined from angular velocity W2 which in turn was computed from appropriate equations similar to those given in the appendix. Curves 610 and 620 intersect at $D_i=0$, but the slope magnitude (and hence the acceleration) for curve 610 is smaller than for curve 620. The maximum acceleration (at $D_i = 0$) for curve 610 is about two times smaller than for curve 620. Since the angular velocity W2 is proportional to V, the acceleration associated with W2 is also about two times smaller for curve 610.

In some embodiments, the plasma system 110 corresponding to curve 610 performs a back-side etch of wafers or individual

In some embodiments, the processing is divided into several stages. For example, in etches of semiconductor wafers, as the wafer becomes thinner, it heats up faster. Therefore, several stages are used. Different stages may have different processing parameters such as velocities and cooling times (the times the wafer spends at $\Theta=0$ for example). In each processing stage, the processing parameters (velocities, etc.) are the same. Each processing stage is sub-divided into two sub-stages. In the first sub-stage, the W1 revolutions are in one direction, and in the second sub-stage, the W1 revolutions are in the other direction. For example, the first stage may include four hundred W2 revolutions. In the first two hundred W2 revolutions, the W1 rotation is in the positive direction; in the next two hundred W2 revolutions, the W1 rotation is in the negative direction. This is repeated in the subsequent stages. The whole process may include thousands of the W2 revolutions, depending on the etching speed and the amount of the material to be removed.

In some embodiments, the direction of the W2 rotation also changes during processing. Thus, some embodiments use any two or more of the four combinations of the W1 and W2 rotations shown in the following table 1:

TABLE 1

Direction of W1 Rotation	Direction of W2 Rotation
positive	positive
positive	negative
negative	positive
negative	negative

In some embodiments, to improve uniformity, the articles are processed only during one half of each W2 revolution. The reasons for this will now be explained with reference to Figs. 8-15. As shown in Fig. 8, wafers 134 sweep a ring-shaped (donut-shaped) area 810 bounded by circles 234C and 234F. In

This leads to processing non-uniformity. At the beginning of path 1210 ($\Theta = \Theta 2$) the plasma has just processed the inner edge 234C (i.e. 134C) of the wafers. At the end of path 1210 ($\Theta = 360° - \Theta 2$), the inner edge 234C re-enters the plasma. Thus, the path 1210 represents the time that the inner edge 234C is allowed to cool before being re-processed. Similarly, path 1220 represents the time that the outer edge 234F is allowed to cool before being re-processed. If the path 1220 is longer, the outer edge cools more, and hence is processed at a slower rate.

To even out the processing rates, in some embodiments the W2 rotation (the rotation of drive 150) is slowed down in path 1210 to allow the inner edge 234C to cool more. However, in path 1210, some portions of the carousel (including the arms 140A and, perhaps, the drive 140) are exposed to the plasma. Therefore, the carousel lifetime is reduced by the heat and active chemicals carried by the plasma.

In other embodiments, the W2 revolutions are accelerated sharply at $\Theta=\Theta 2$ (Fig. 14). The linear velocity of the wafers increases, for example, by 100-150%, and then sharply returns to 0 or some other suitable value (as needed for cooling) when Θ is near 360°. Thus, the wafer processing is substantially prevented when Θ is between 180° and 360°. Consequently, the coding is more uniform, and the processing uniformity is increased.

In Fig. 15, the angular velocity W2 is increased for Θ between 0 and 180° to prevent wafer processing. The wafer is processed between 180° and 360°.

The above embodiments illustrate but do not limit the invention. The invention is not limited to any particular shape or size of opening 114-O or plasma footprint 120F. In some embodiments, the shape and dimensions of opening 114-O vary during processing. In some embodiments, the velocity W1 varies during processing. In some embodiments, drive 140 is omitted. Plasma source 114 moves radially along a rotation

APPENDIX

$$W2(t) = \partial\Theta/\partial t$$

$$\int_0^T W2(t)dt = 2\pi$$

$$P(r1) = (1/2)*\pi*r1*\int_0^T\int_0^{2\pi} p(\rho(\beta),\varphi(t,\beta))dtd\beta,\ R1\le r1\le LS$$

$$\rho(\beta) = (R2^2+ r1^2-2*R2*r1*\cos(\beta))^{1/2}$$

$$\varphi(t,\beta) = \Theta(t) + \cos^{-1}((R2^2+\rho^2(\beta)-r1^2)/(2*R2*\rho(\beta)))$$

where:

t is time; T is the duration of one revolution of second drive 150;

P(r1) is the desired process result on the surface of the wafer 134 along the radius r1 of the first drive 140;

$p(\rho(\beta),\varphi(t,\beta))$ is the distribution of the plasma treatment intensity within the plasma footprint 120F at the surface of wafer 134 at a point having polar coordinates (ρ,φ) in the polar coordinate system having an origin on the axis 150X;

β is the angular position of the arm 140A relative to any predetermined direction in the plane of wafer 130 (i.e. perpendicular to rotation axes 140X, 150X).

includes rotating a second axis around the first axis as the article rotates around the second axis.

7. The method of Claim 6 wherein in the first period of time, as the first axis rotates in the first direction, the second axis rotates in a third direction, and in the second period of time, as the first axis rotates in the second direction, the second axis rotates in a fourth direction opposite from the third direction.

8. The method of Claim 6 wherein in the first period of time, as the first axis rotates in the first direction, the second axis rotates in a third direction, and in the second period of time, as the first axis rotates in the second direction, the second axis rotates in the third direction.

9. The method of Claim 6 wherein the first and second axes are spaced from the article.

10. The method of Claim 1 wherein the plasma processing takes place at atmospheric pressure.

11. The method of Claim 1 wherein during the rotational motion in the first direction, the article enters the plasma at a first edge portion of the article and exits the plasma at a second edge portion of the article; and

during the rotational motion in the second direction, the article enters the plasma at the second edge portion and exits the plasma at the first edge portion.

12. The method of Claim 1 wherein the article is a semiconductor wafer.

13. An apparatus for processing an article with plasma, the apparatus comprising:

a plasma source; and

period of time, as the first drive rotates in the second direction, the second drive rotates in a fourth direction opposite from the third direction.

20. The apparatus of Claim 18 wherein in the first period of time, as the first drive rotates in the first direction, the second drive rotates in a third direction, and in the second period of time, as the first drive rotates in the second direction, the second drive rotates in the third direction.

21. The apparatus of Claim 18 wherein the article is to be laterally spaced from the first and second drives.

22. The apparatus of Claim 13 wherein the plasma processing takes place at atmospheric pressure.

23. The apparatus of Claim 13 wherein during the rotational motion in the first direction, the article is to enter the plasma at a first edge portion of the article and to exit the plasma at a second edge portion of the article; and

during the rotational motion in the second direction, the article is to enter the plasma at the second edge portion and to exit the plasma at the first edge portion.

24. The apparatus of Claim 13 wherein the article is a semiconductor wafer.

25. The apparatus of Claim 13 in combination with the article.

26. A method for processing an article with plasma, the method comprising:

generating plasma;

rotating an article around a first axis, and rotating the first axis around a second axis, so that the article gets processed with the plasma;

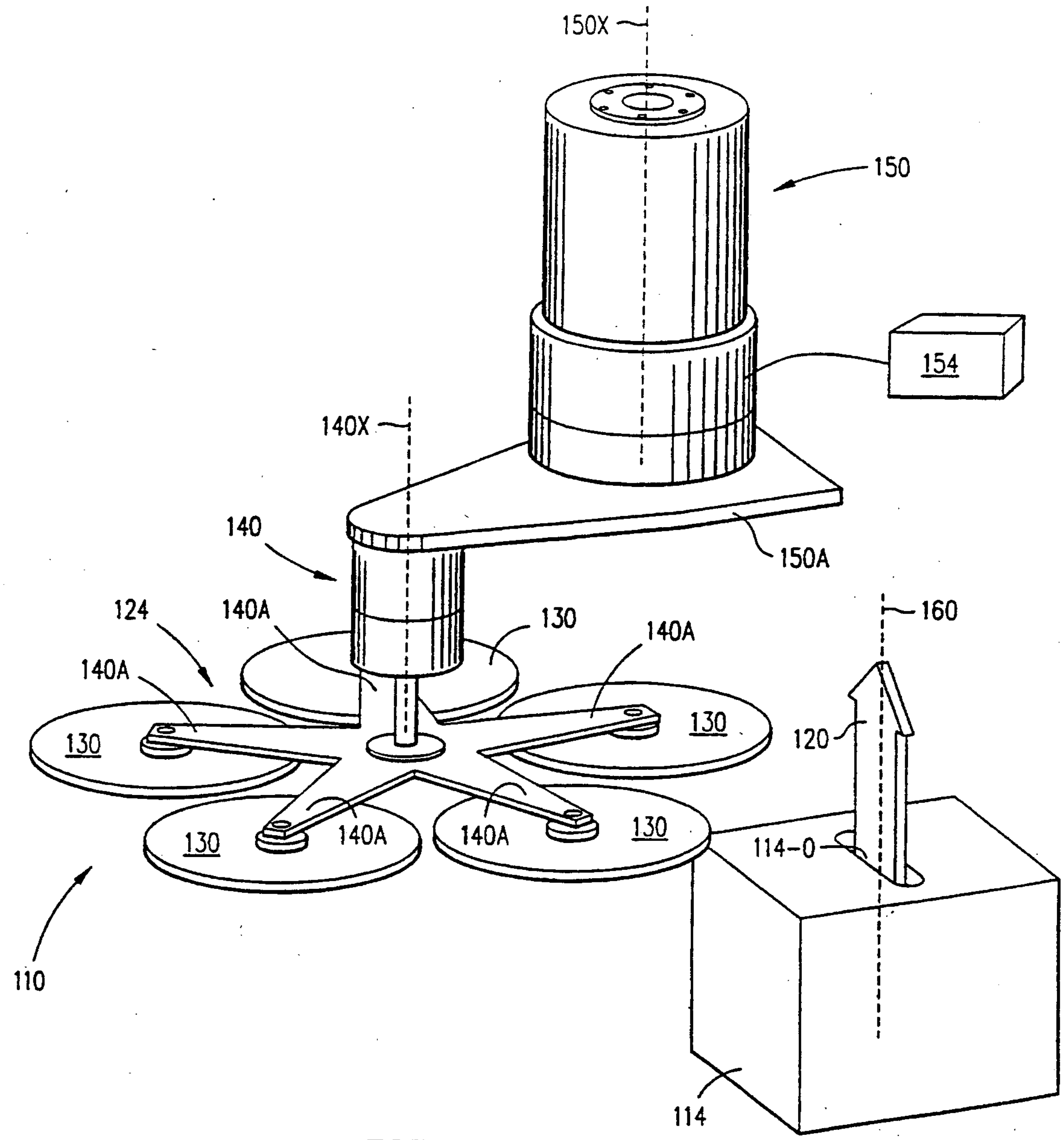

150X
150
154
140X
140
150A
124
140A
130
140A
160
140A
130
130
120
130
140A
140A
130
114-0
110
114

FIG. 1

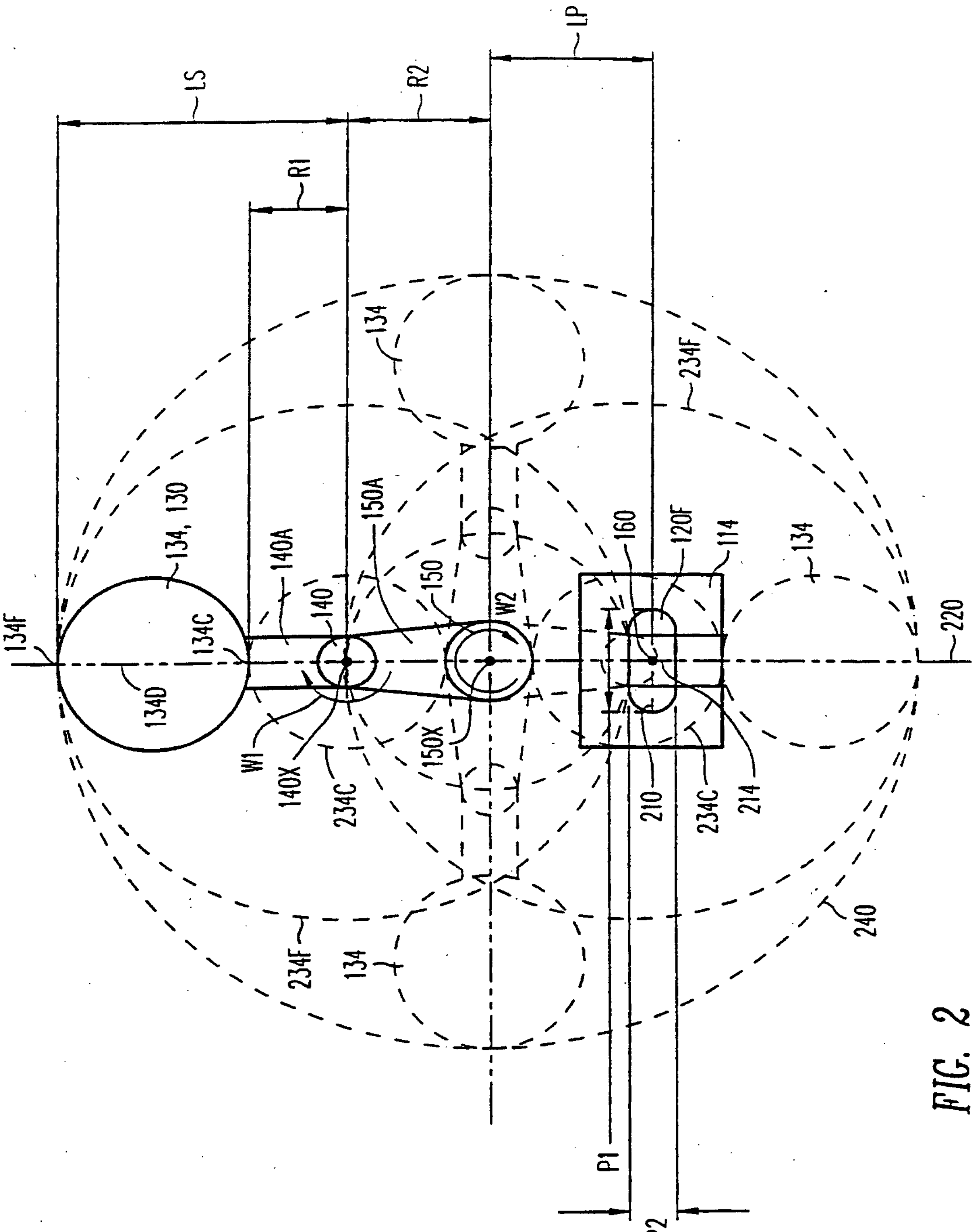
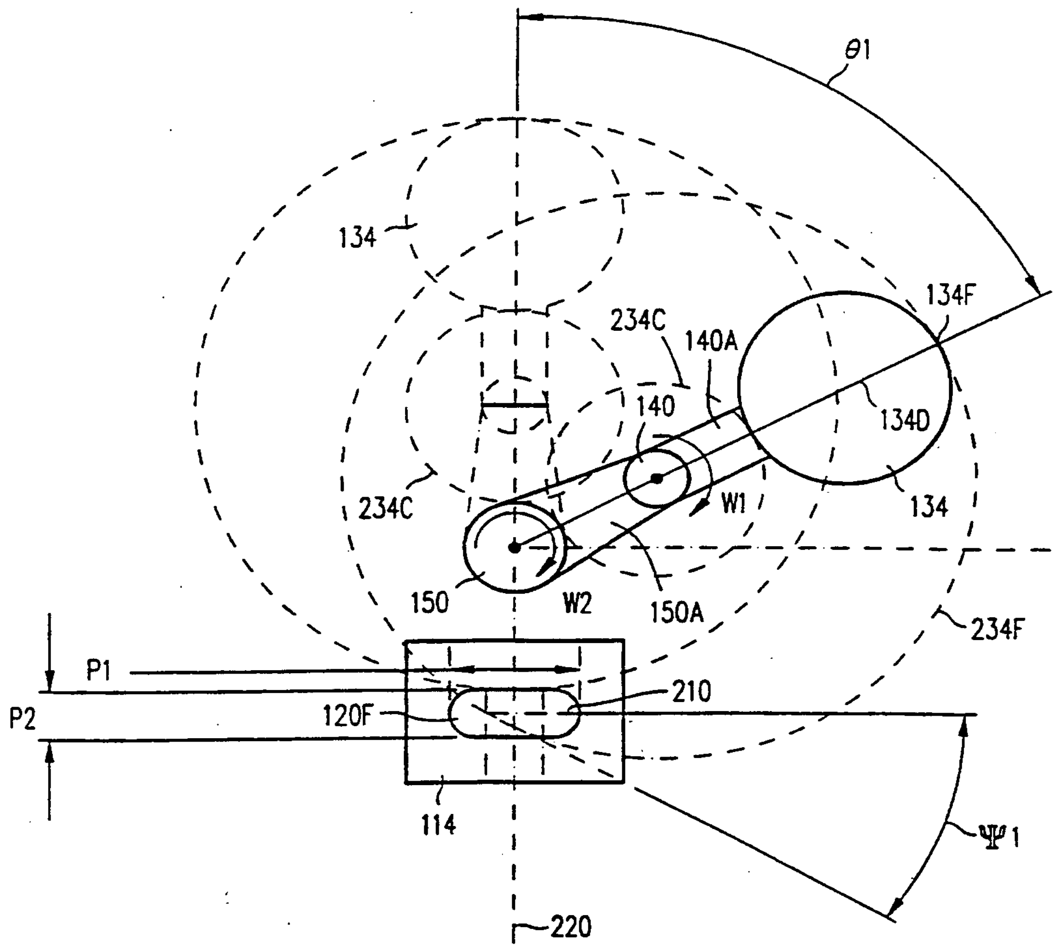

LS
R2
LP
R1
134
234F
134, 130
140A
150A
150
160
120F
114
134
134F
134C
140
W2
220
134D
W1
140X
234C
150X
210
234C
214
240
234F
134
P1
P2

FIG. 2


θ1
134
134F
234C
140A
140
134D
234C
W1
134
150
W2
150A
234F
P1
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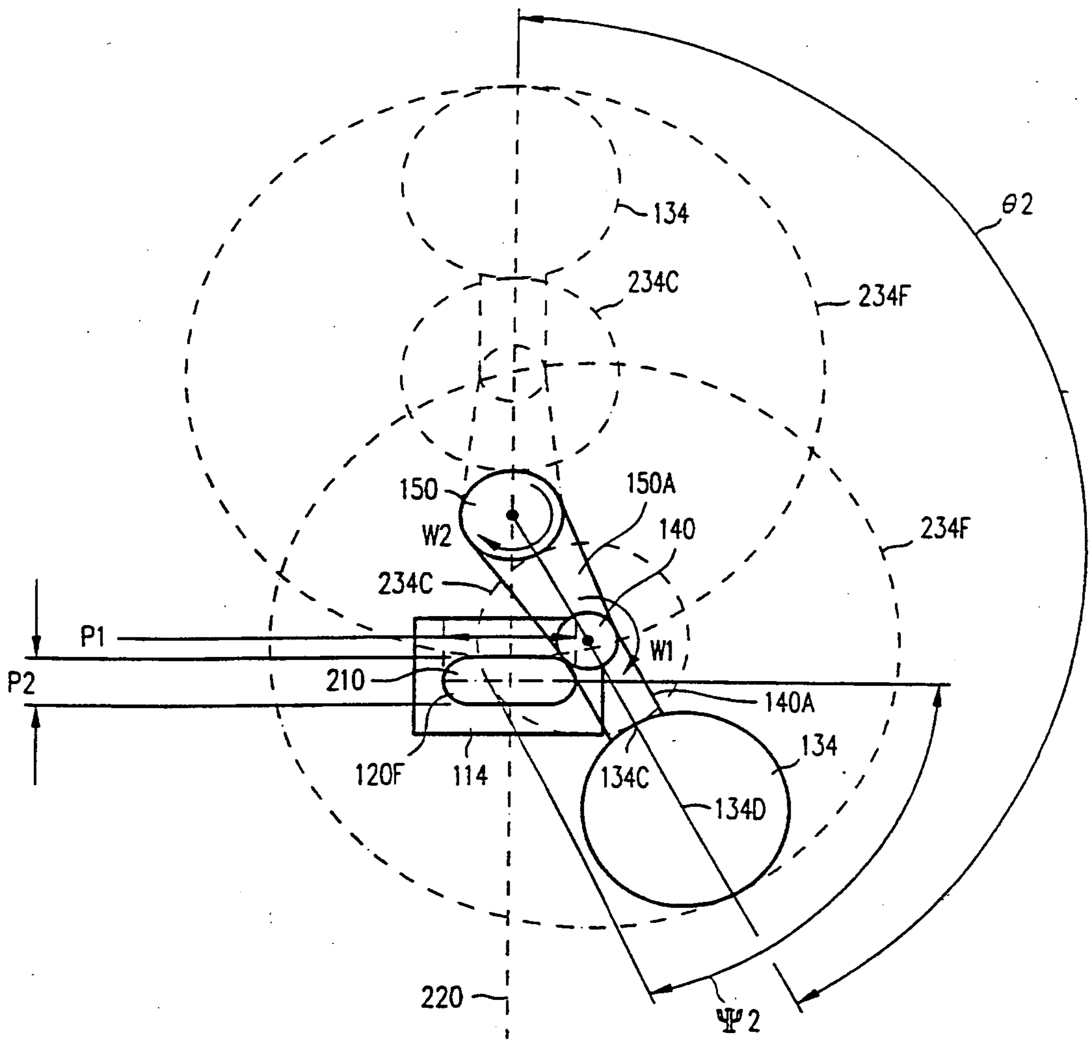
P2
120F
114
Ψ1
220

FIG. 3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234F
θ2
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150A
140
W2
234F
234C
P1
W1
P2
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140A
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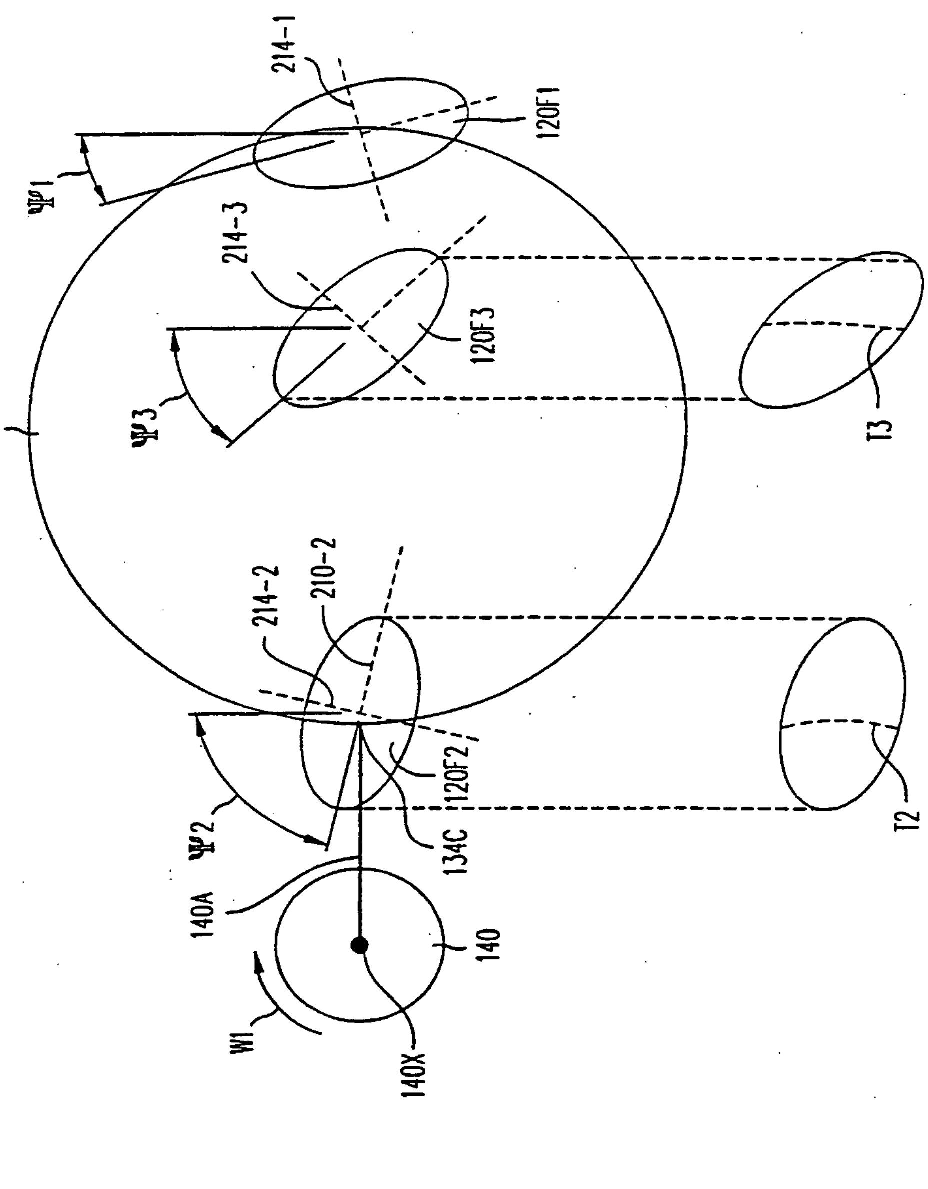
120F
114
134C
134D
220
Ψ2

FIG. 4


214-1
120F1
Ψ1
214-3
120F3
Ψ3
134
T3
214-2
210-2
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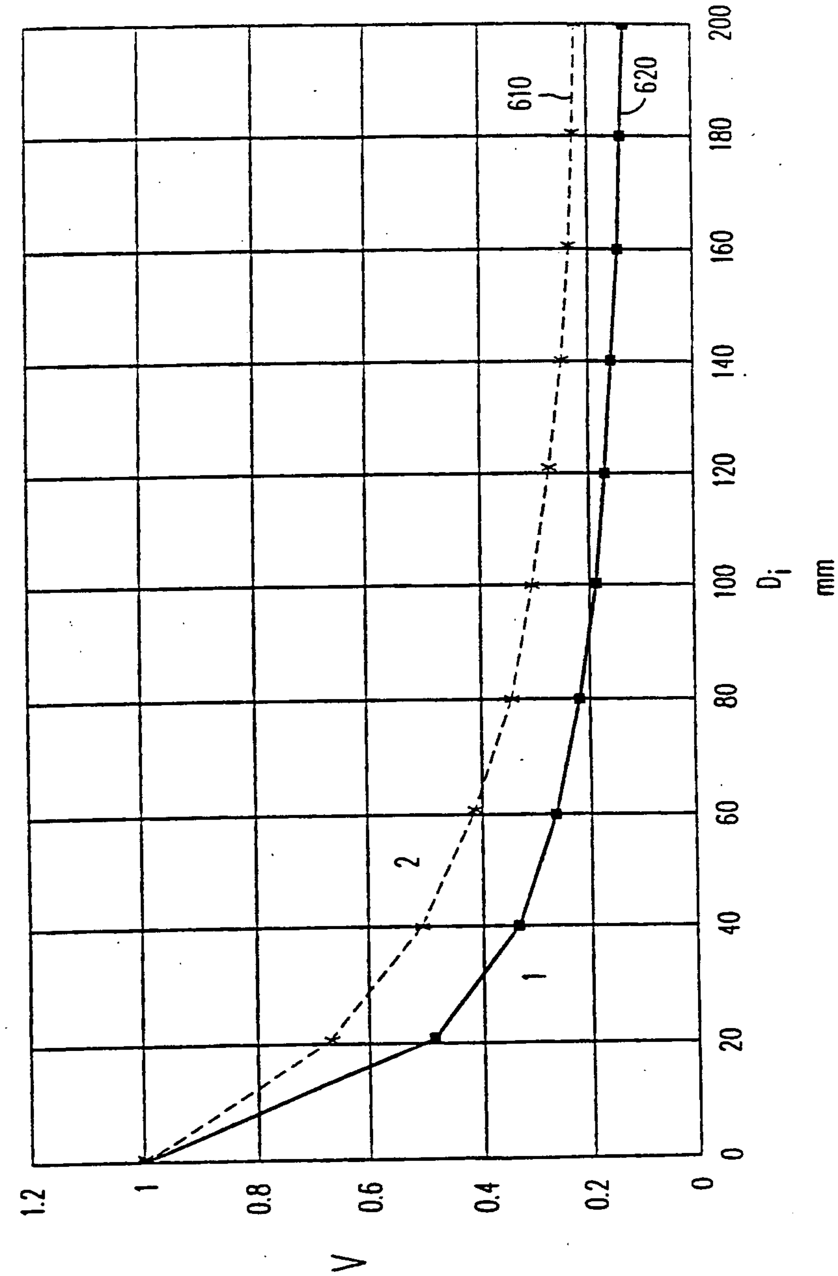
Ψ2
140A
140
W1
140X
T2

FIG. 5


V
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1
0.8
0.6
0.4
0.2
0
0
20
40
60
80
100
120
140
160
180
200
D_i
mm
1
2
610
620

FIG. 6

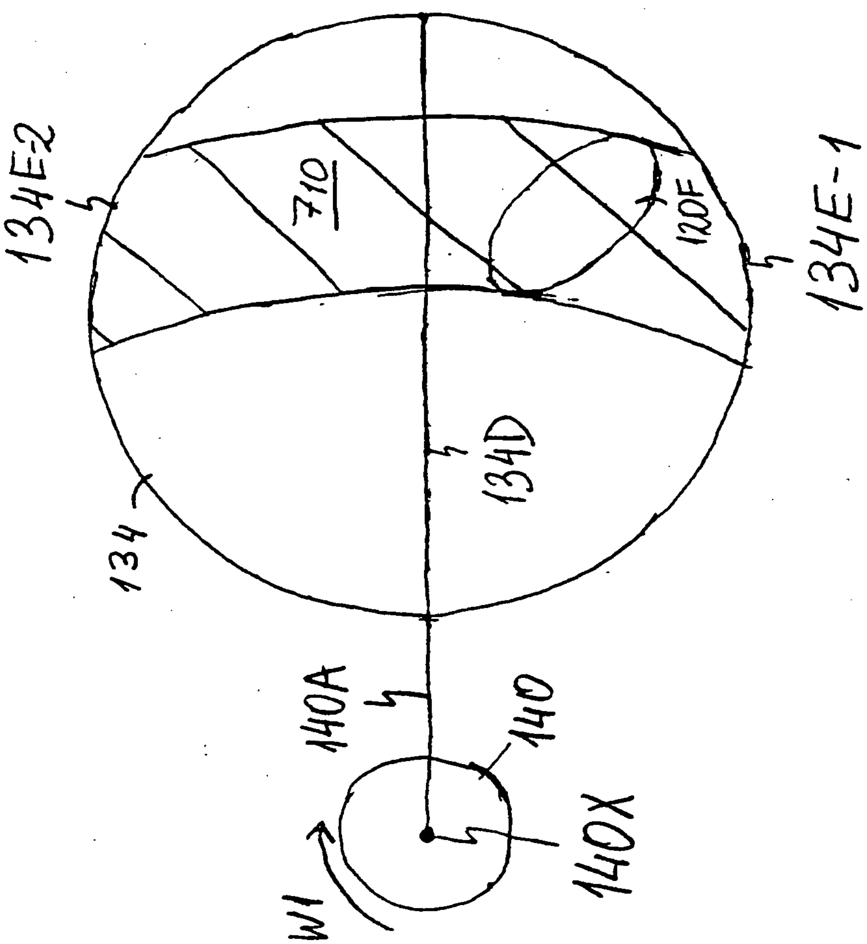
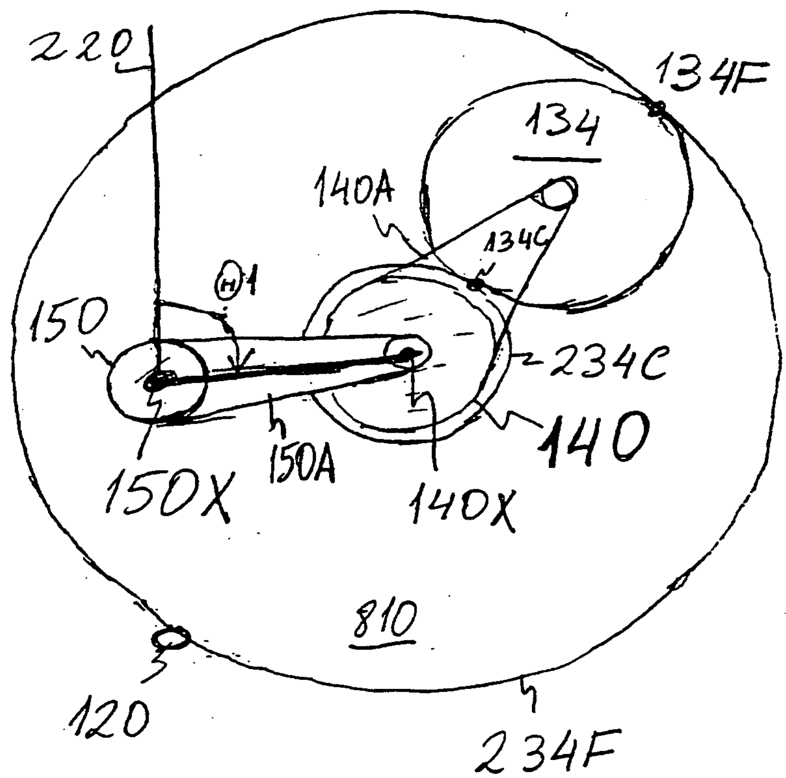


FIG. 7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134F
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140A
134C
Θ1
150
234C
140
150X
150A
140X
810
120
234F

FIG. 8

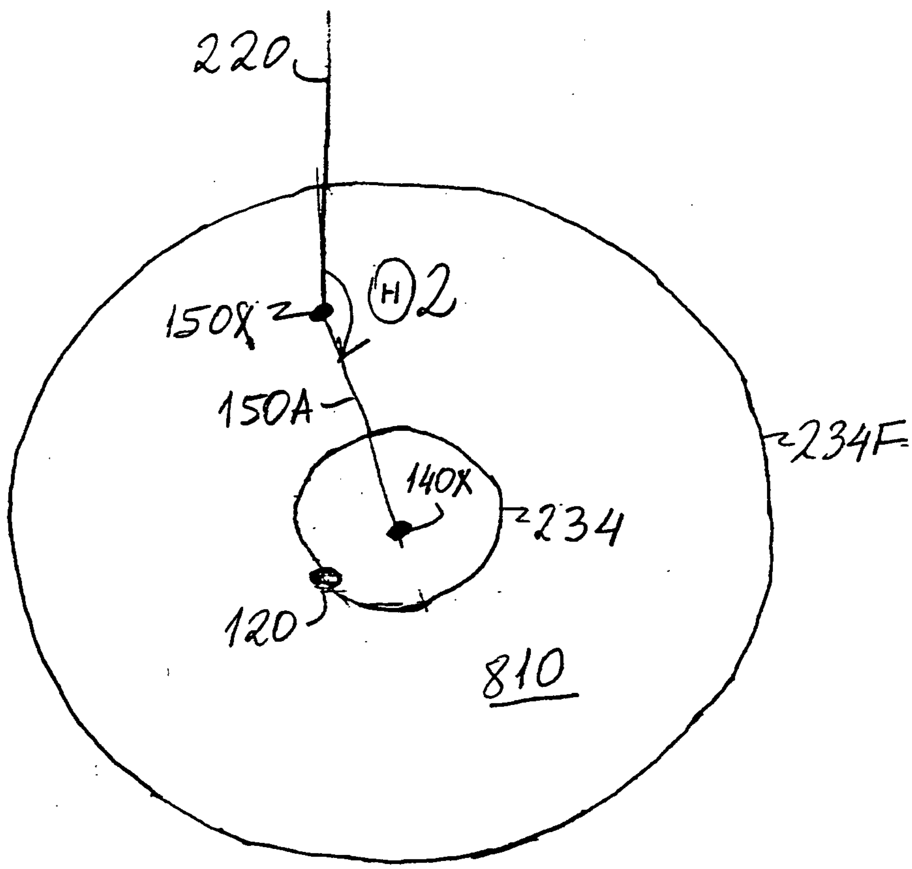


FIG. 9

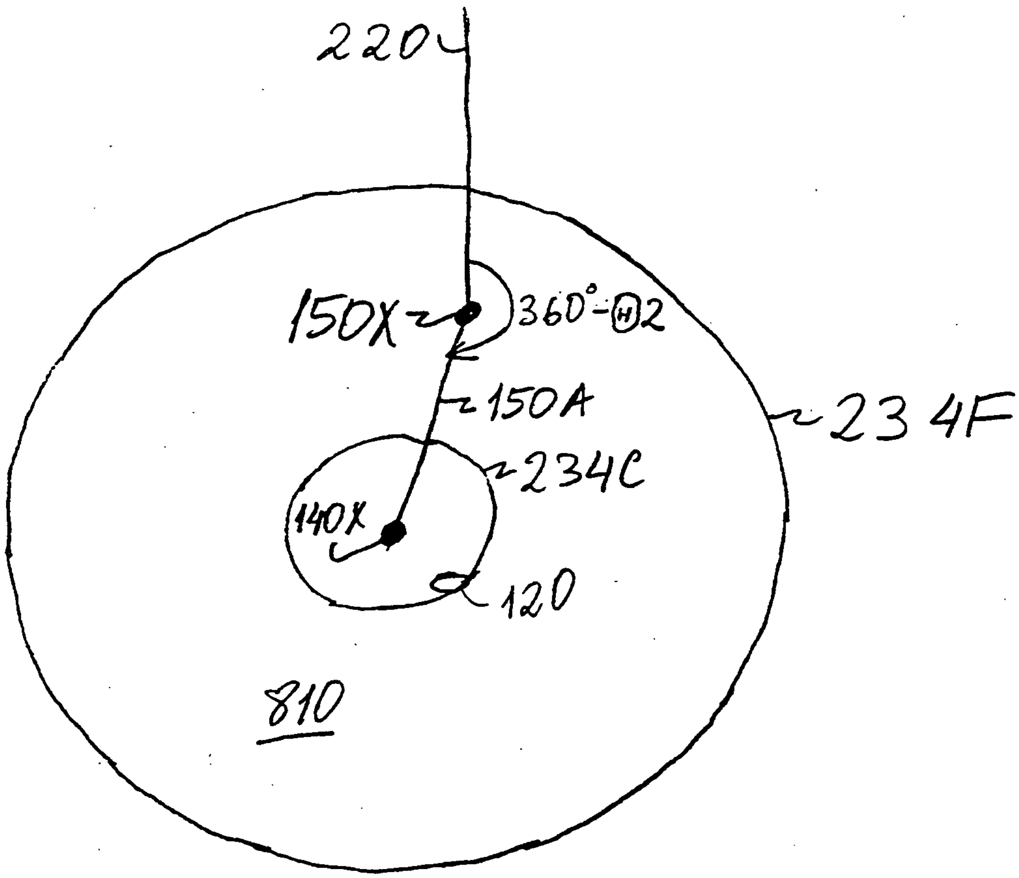


FIG. 10

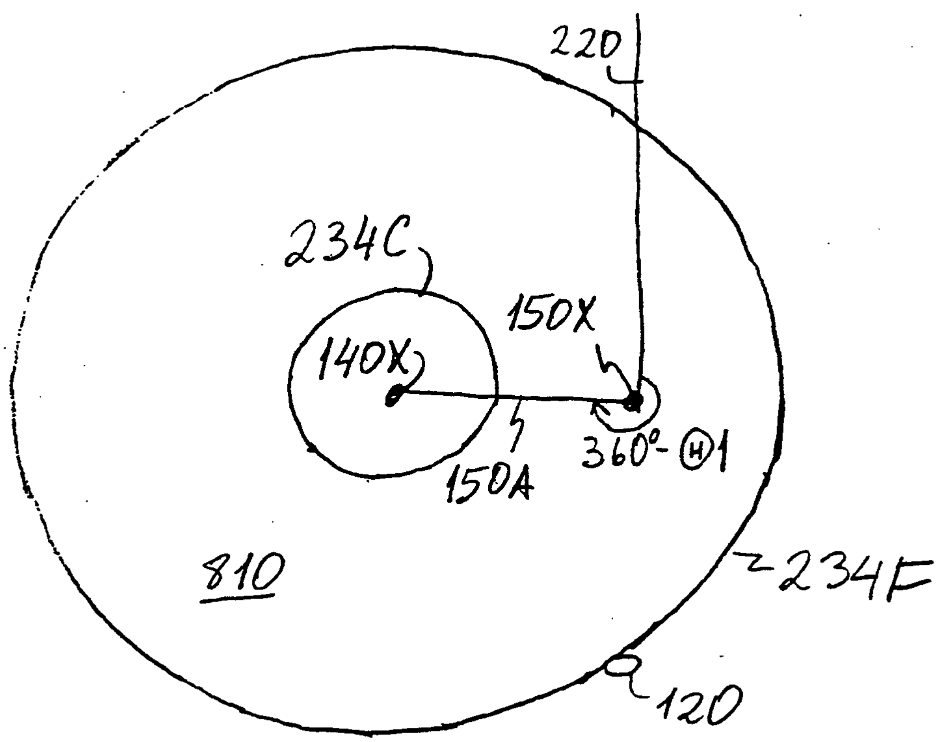


FIG. 11

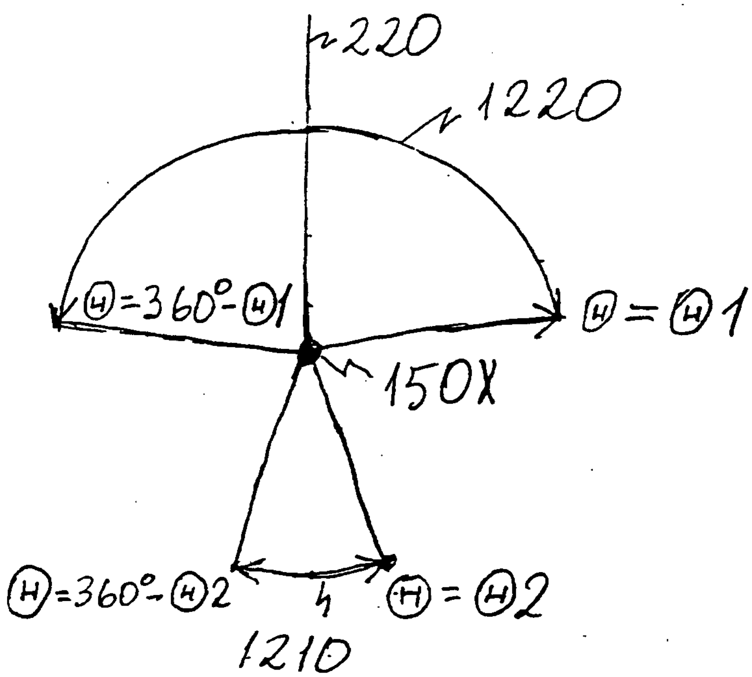


FIG. 12

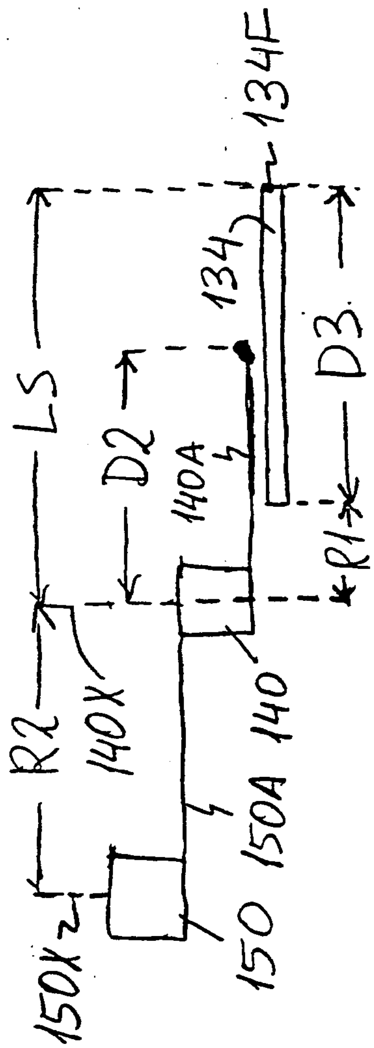
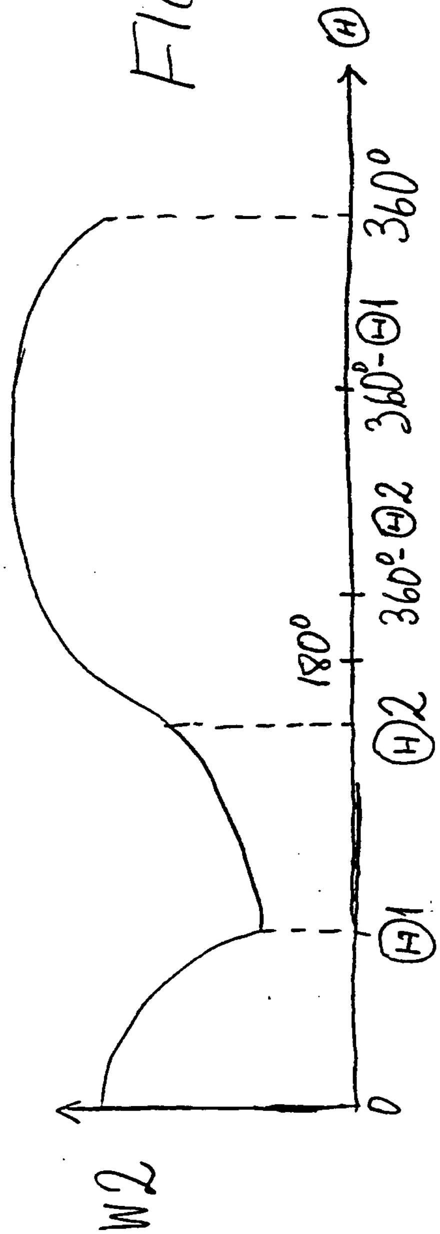


FIG. 13

FIG. 14



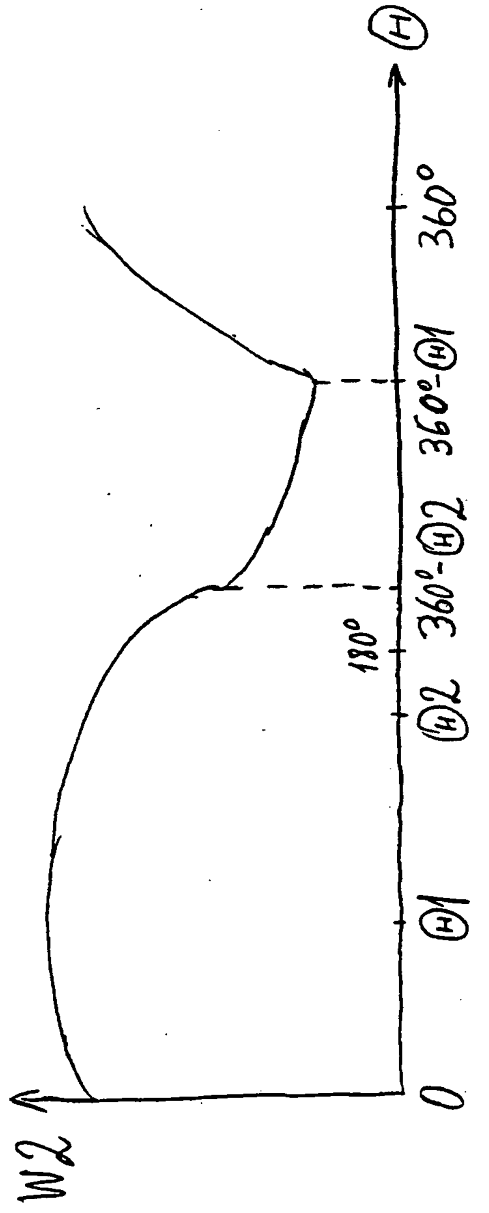


FIG. 15

INTERNATIONAL SEARCH REPORT

International Application No
PCT/US 00/13976

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 H01L21/00 H01J37/32

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 H01L H01J H05H C23C

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

WPI Data, PAJ, EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
P,Y	WO 99 26796 A (TRUSI TECHNOLOGIES LLC) 3 June 1999 (1999-06-03)	1,2,5, 10, 12-14, 17,18, 21,22,24 26,29
A	abstract; figures	

Y	US 5 029 555 A (DIETRICH HANS P ET AL) 9 July 1991 (1991-07-09)	1,2,5, 10, 12-14, 17,18, 21,22,24
	column 2, line 43 - line 60; figures	

A	US 5 308 461 A (AHONEN ROBERT G) 3 May 1994 (1994-05-03) column 3, line 1 -column 4, line 10; figures 1,2	1,13,26, 29

	-/--	

[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

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26 September 2000	02/10/2000

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1

INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No
PCT/US 00/13976

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